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# Uniqueness results for pseudomonotone problems with $p > 2$

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**Abstract.** We consider a pseudomonotone operator, the model of which is  $-div(b(x, u)|\nabla u|^{p-2}\nabla u)$  with  $1 < p < +\infty$  and  $b(x, s)$  a Lipschitz continuous function in  $s$  which satisfies  $0 < \alpha \leq b(x, s) \leq \beta < +\infty$ . We show the comparison principle (and therefore the uniqueness for the Dirichlet problem) in two particular cases, namely the one-dimensional case, and the case where at least one of the right-hand sides does not change sign. In our knowledge these results are new for  $p > 2$ . Full detailed proofs are given in the present Note. The results continue to hold when  $\Omega$  is unbounded. © XXXX Académie des sciences/Éditions scientifiques et médicales Elsevier SAS

**Résultats d'unicité pour des problèmes pseudomonotones avec  $p > 2$**

**Résumé.** Nous considérons un opérateur pseudomonotone du type  $-div(b(x, u)|\nabla u|^{p-2}\nabla u)$ , avec  $1 < p < +\infty$  et  $b(x, s)$  une fonction Lipschitzienne en  $s$  qui vérifie  $0 < \alpha \leq b(x, s) \leq \beta < +\infty$ . Nous démontrons que cet opérateur satisfait le principe de comparaison (et donc qu'on a unicité pour le problème de Dirichlet) dans deux cas particuliers : en dimension 1, et dans le cas où au moins l'un des deux seconds membres ne change pas de signe. A notre connaissance, ces résultats sont nouveaux quand  $p > 2$ . Les démonstrations complètes sont données dans cette Note. Les résultats restent valides quand  $\Omega$  est non borné. © XXXX Académie des sciences/Éditions scientifiques et médicales Elsevier SAS

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## Version française abrégée

Dans cette Note, nous démontrons deux résultats d'unicité pour la solution du problème de Dirichlet pseudomonotone

$$u - U_0 \in W_0^{1,p}(\Omega), \quad \int_{\Omega} a(x, u, \nabla u) \nabla v \, dx = \langle f, v \rangle, \quad \forall v \in W_0^{1,p}(\Omega), \quad (1)$$

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Note présentée par XXX

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quand  $\Omega$  est un ouvert borné de  $\mathbb{R}^N$  (aucune hypothèse de régularité n'est faite sur le bord de  $\partial\Omega$ ), quand  $1 < p < +\infty$ , et quand la fonction  $a : \Omega \times \mathbb{R} \times \mathbb{R}^N \rightarrow \mathbb{R}^N$  est une fonction de Carathéodory qui vérifie les hypothèses (6), (7) et (8) de la version anglaise.

De façon précise, nous démontrons sous ces hypothèses le principe de comparaison, c'est-à-dire que les hypothèses (3) et (4) de la version anglaise impliquent (5) (ce qui évidemment entraîne l'unicité de la solution de (1)) dans les deux cas suivants : le cas où  $N = 1$ , et le cas où dans (3),  $f_1$  ou  $f_2$  est de signe constant. Un résultat plus fort est connu quand  $1 < p \leq 2$  (voir [2]), à savoir le principe de comparaison (et donc l'unicité) dans le cas où la fonction  $a$  vérifie les hypothèses (6) et (2) de la version anglaise et une hypothèse de coercivité, et ce sans restriction sur la dimension ni sur le signe du second membre. En revanche nos résultats semblent nouveaux quand  $p > 2$ . Les démonstrations, qui sont intégralement données dans la Section 2 de cette Note, reposent sur deux lemmes (Lemma 2.1 et Lemma 2.2 de la version anglaise) qui ont leur intérêt propre. Ils utilisent de façon essentielle l'hypothèse (8), qui n'est pas l'hypothèse de croissance classiquement faite sur la fonction  $a$ . Enfin dans la brève Section 3, nous expliquons comment modifier nos énoncés pour que le principe de comparaison et les résultats d'unicité restent valables, avec les mêmes démonstrations, dans le cas d'ouverts non bornés.

## 1. Introduction and main results

In this Note we prove two uniqueness results for the solution of the Dirichlet pseudomonotone problem

$$u - U_0 \in W_0^{1,p}(\Omega), \quad \int_{\Omega} a(x, u, \nabla u) \nabla v \, dx = \langle f, v \rangle, \quad \forall v \in W_0^{1,p}(\Omega), \quad (1)$$

where  $\Omega$  is a bounded open set of  $\mathbb{R}^N$  (no smoothness assumption is made on  $\partial\Omega$ ) (see Section 3 for the case where  $\Omega$  is unbounded),  $a : \Omega \times \mathbb{R} \times \mathbb{R}^N \rightarrow \mathbb{R}^N$  is a Carathéodory function which satisfies coerciveness and growth conditions, so that the operator  $u \rightarrow -\operatorname{div} a(x, u, \nabla u)$  is pseudomonotone in the Sobolev space  $W_0^{1,p}(\Omega)$ ,  $f$  belongs to  $W^{-1,p'}(\Omega)$  and  $U_0$  to  $W^{1,p}(\Omega)$ . The existence of at least one solution for this problem is known since the celebrated result of J. Leray and J.-L. Lions (see [10], [11]). When  $1 < p \leq 2$ , and when the function  $a(x, s, \xi)$  is strongly monotone in  $\xi$  (condition (6) below) and satisfies the (weighted) Lipschitz continuity condition in  $s$

$$|a(x, s, \xi) - a(x, s', \xi)| \leq (\gamma|\xi|^{p-1} + \gamma_0(|s| + |s'|)^{p-1} + |\ell(x)|) |s - s'|, \quad (2)$$

a.e.  $x \in \Omega$ , for every  $s, s' \in \mathbb{R}$ , for every  $\xi \in \mathbb{R}^N$ , with  $\gamma > 0$ ,  $\gamma_0 \geq 0$  and  $\ell \in L^{p'}(\Omega)$ , it is proved in [2]<sup>1</sup>, [9] (see also [1], [4], [5], [12], [13]) that the operator  $u \rightarrow -\operatorname{div} a(x, u, \nabla u)$  satisfies the comparison principle in the following sense: when

$$u_i \in W^{1,p}(\Omega), \quad f_i \in W^{-1,p'}(\Omega), \quad -\operatorname{div} a(x, u_i, \nabla u_i) = f_i \text{ in } \mathcal{D}'(\Omega), \quad (3)$$

and when

$$f_1 \leq f_2 \text{ in } \Omega, \quad u_1 \leq u_2 \text{ on } \partial\Omega, \quad (4)$$

(where the first assertion has to be understood in the sense of distributions or equivalently in the sense of  $W^{-1,p'}(\Omega)$ , and the second one as  $(u_1 - u_2)^+ \in W_0^{1,p}(\Omega)$ ), then one has

$$u_1 \leq u_2 \text{ in } \Omega. \quad (5)$$

In particular, uniqueness holds for problem (1).

<sup>1</sup>Let us explicitly note that there is a mistake in the writing of some of the assumptions in [2]: indeed there is no function which satisfies assumption (3) of [2] when  $p < 2$  (just take  $\xi \neq 0$  fixed and let  $\eta$  tend to zero). Nevertheless the results of [2] are correct and can be proved by (essentially) the proof used there, once assumptions (1) and (3) of [2] are replaced by  $a(x, s, \xi)\xi \geq \alpha|\xi|^p - \gamma|s|^\sigma - \theta(x)$  with  $\sigma < p$  and by assumption (6) of the present paper.

## Uniqueness results for pseudomonotone problems with $p > 2$

In the present paper, we assume  $1 < p < +\infty$  (although it follows from the comparison principle stated just above that our results are not new when  $1 < p \leq 2$ ) and that  $a$  satisfies the following assumptions: there exist  $\alpha > 0, \beta > 0, \gamma > 0$  such that a.e.  $x \in \Omega$ , for every  $s, s' \in \mathbb{R}$ , for every  $\xi, \xi' \in \mathbb{R}^N$ ,

$$(a(x, s, \xi) - a(x, s, \xi'))(\xi - \xi') \geq \alpha(|\xi| + |\xi'|)^{p-2}|\xi - \xi'|^2, \quad (6)$$

$$|a(x, s, \xi) - a(x, s', \xi)| \leq \gamma|\xi|^{p-1}|s - s'|, \quad (7)$$

$$|a(x, s, \xi)| \leq \beta|\xi|^{p-1}. \quad (8)$$

Observe that assumption (7) is less general than (2), and that assumption (8) is less general than the growth condition which is classically assumed on  $a$ , namely  $|a(x, s, \xi)| \leq \beta|\xi|^{p-1} + \beta_0|s|^{p-1} + |\ell(x)|$ .

The model example for the function  $a$  is  $a(x, s, \xi) = b(x, s)|\xi|^{p-2}\xi$ , where  $b$  is a Carathéodory function which is Lipschitz continuous in  $s$  and satisfies  $0 < \alpha \leq b(x, s) \leq \beta < +\infty$ . In the very special case where  $b(x, s) = c(x)g(s)$ , the comparison principle for (1) is easily proved by using the change of unknown function  $v(x) = \int_0^{u(x)} g(t)^{\frac{1}{p-1}} dt$ , which transforms in this case the pseudomonotone problem (1) into a strongly monotone one. However, in our knowledge, if  $b$  does not have this special form and only satisfies assumptions (6), (7) and (8), the comparison principle (and uniqueness) for (1) is an open problem for  $p > 2$ . Here we prove that the comparison principle and uniqueness hold in two particular cases: in the one dimensional case, and when the sign of  $f_1$  and/or  $f_2$  is constant. Unfortunately the general case remains an open problem.

**THEOREM 1.1.** – Assume  $N = 1$  and that (6), (7) and (8) hold. Let  $u_1, u_2, f_1, f_2$  satisfy (3) and (4). Then  $u_1 \leq u_2$  a.e. in  $\Omega$ . In particular, uniqueness holds for problem (1) when  $N = 1$ .

**THEOREM 1.2.** – Assume that (6), (7) and (8) hold. Let  $u_1, u_2, f_1, f_2$  satisfy (3) and (4). If the sign of  $f_1$  and/or the sign of  $f_2$  is constant in  $\Omega$ , then  $u_1 \leq u_2$  a.e. in  $\Omega$ . In particular, uniqueness holds for problem (1) when the sign of  $f$  is constant in  $\Omega$ .

## 2. Proofs

In this Section we give complete proofs of the above results. We begin with two Lemmas which have their own interest.

**LEMMA 2.1.** – Assume that (6), (7) and (8) hold. Let  $u_1, u_2, f_1, f_2$  satisfy (3) and (4). Then, for every  $\varepsilon > 0$ , we have

$$\begin{cases} \alpha \int_{\{0 < u_1 - u_2 < \varepsilon\}} (|\nabla u_1| + |\nabla u_2|)^{p-2} |\nabla(u_1 - u_2)|^2 dx \leq \\ \leq \gamma \varepsilon \int_{\{0 < u_1 - u_2 < \varepsilon\}} \min\{|\nabla u_1|, |\nabla u_2|\}^{p-1} |\nabla(u_1 - u_2)| dx. \end{cases} \quad (9)$$

Moreover we have

$$\lim_{\varepsilon \rightarrow 0} \frac{1}{\varepsilon^2} \int_{\{0 < u_1 - u_2 < \varepsilon\}} (|\nabla u_1| + |\nabla u_2|)^{p-2} |\nabla(u_1 - u_2)|^2 dx = 0. \quad (10)$$

*Proof.* – For  $\varepsilon > 0$ , we define  $T_\varepsilon : \mathbb{R} \rightarrow \mathbb{R}$  as the usual truncation at height  $\varepsilon$ , namely

$$T_\varepsilon(s) = s \text{ if } |s| \leq \varepsilon, \quad T_\varepsilon(s) = \varepsilon \operatorname{sgn}(s) \text{ if } |s| \geq \varepsilon. \quad (11)$$

Taking  $T_\varepsilon(u_1 - u_2)^+$  as test function in (3) for  $i = 1$  and  $i = 2$ , making the difference, denoting  $U_1^\varepsilon = \{0 < u_1 - u_2 < \varepsilon, |\nabla u_1(x)| \leq |\nabla u_2(x)|\}$ ,  $U_2^\varepsilon = \{0 < u_1 - u_2 < \varepsilon, |\nabla u_2(x)| < |\nabla u_1(x)|\}$ , then adding and subtracting in the integral on  $U_1^\varepsilon$  the term  $a(x, u_2, \nabla u_1) \nabla(u_1 - u_2)$  and in the integral on  $U_2^\varepsilon$  the term  $a(x, u_1, \nabla u_2) \nabla(u_1 - u_2)$ , we get, for every  $\varepsilon > 0$

$$\begin{aligned} & \int_{U_1^\varepsilon} (a(x, u_2, \nabla u_1) - a(x, u_2, \nabla u_2)) \nabla(u_1 - u_2) dx + \\ & + \int_{U_2^\varepsilon} (a(x, u_1, \nabla u_1) - a(x, u_1, \nabla u_2)) \nabla(u_1 - u_2) dx \leq \\ & \leq - \int_{U_1^\varepsilon} (a(x, u_1, \nabla u_1) - a(x, u_2, \nabla u_1)) \nabla(u_1 - u_2) dx - \\ & - \int_{U_2^\varepsilon} (a(x, u_1, \nabla u_2) - a(x, u_2, \nabla u_2)) \nabla(u_1 - u_2) dx. \end{aligned}$$

From (6) and (7) we obtain (9). Using in (9)  $\min\{|\nabla u_1|, |\nabla u_2|\} \leq |\nabla u_1| + |\nabla u_2|$ , Cauchy-Schwartz's inequality and the fact that the measure of the set  $\{0 < u_1 - u_2 < \varepsilon\}$  tends to zero with  $\varepsilon$  yields (10).  $\square$

LEMMA 2.2. – Assume that (6), (7) and (8) hold. Let  $u_1, u_2, f_1, f_2$  satisfy (3) and (4). Then for every  $\varphi \in W^{1,p}(\Omega) \cap L^\infty(\Omega)$  and for  $T_\varepsilon$  defined by (11), we have

$$\int_{\{u_2 < u_1\}} a(x, u_i, \nabla u_i) \nabla \varphi dx = \lim_{\varepsilon \rightarrow 0} \langle f_i, \frac{T_\varepsilon(u_1 - u_2)^+}{\varepsilon} \varphi \rangle, \quad i \in \{1, 2\}. \quad (12)$$

*Proof.* – For  $\varphi \in W^{1,p}(\Omega) \cap L^\infty(\Omega)$  and  $i \in \{1, 2\}$ , we take  $\varphi T_\varepsilon(u_1 - u_2)^+ / \varepsilon$  as test function in (3). This gives

$$\begin{cases} \int_{\Omega} a(x, u_i, \nabla u_i) \nabla \varphi \frac{T_\varepsilon(u_1 - u_2)^+}{\varepsilon} dx + \frac{1}{\varepsilon} \int_{\{0 < u_1 - u_2 < \varepsilon\}} a(x, u_i, \nabla u_i) \nabla(u_1 - u_2) \varphi dx = \\ = \langle f_i, \frac{T_\varepsilon(u_1 - u_2)^+}{\varepsilon} \varphi \rangle. \end{cases} \quad (13)$$

We easily pass to the limit in the first term of (13) by using Lebesgue's dominated convergence theorem. For the second term of (13), using (8),  $|\nabla u_i|^{p-1} \leq (|\nabla u_1| + |\nabla u_2|)^{p-1}$  and Cauchy-Schwartz's inequality, we get

$$\begin{aligned} & \left| \frac{1}{\varepsilon} \int_{\{0 < u_1 - u_2 < \varepsilon\}} a(x, u_i, \nabla u_i) \nabla(u_1 - u_2) \varphi dx \right| \leq \beta \|\varphi\|_{L^\infty(\Omega)} \\ & \left( \int_{\{0 < u_1 - u_2 < \varepsilon\}} (|\nabla u_1| + |\nabla u_2|)^p dx \right)^{\frac{1}{2}} \left( \frac{1}{\varepsilon^2} \int_{\{0 < u_1 - u_2 < \varepsilon\}} (|\nabla u_1| + |\nabla u_2|)^{p-2} |\nabla(u_1 - u_2)|^2 dx \right)^{\frac{1}{2}}, \end{aligned}$$

which tends to zero by (10). This implies (12).  $\square$

### Uniqueness results for pseudomonotone problems with $p > 2$

*Remark 1.* – In Lemma 2.2, we easily pass to the limit in the right-hand side of (12) if  $f_1$  and  $f_2$  belong to  $L^{p'}(\Omega)$ . In such a case,  $u_i$  satisfies

$$-\operatorname{div}(a(x, u_i, \nabla u_i) \chi_{\{u_2 < u_1\}}) = f_i \chi_{\{u_2 < u_1\}} \text{ in } \mathcal{D}'(\Omega), \quad (14)$$

$$a(x, u_i, \nabla u_i) \chi_{\{u_2 < u_1\}} n = 0 \text{ on } \partial\Omega, \quad (15)$$

where  $n$  is the exterior normal vector to  $\partial\Omega$ . Assertion (14) has been proved in [3] under stronger assumptions. Since  $f_i \chi_{\{u_2 < u_1\}} \in L^{p'}(\Omega)$ , assertion (15) is not only formal but takes place in  $X' = W^{-(1-\frac{1}{p}), p'}(\partial\Omega)$ , the dual space of  $X = W^{1-\frac{1}{p}, p}(\partial\Omega)$ , when the boundary  $\partial\Omega$  is sufficiently smooth for the functions of  $W^{1, p}(\Omega)$  to have traces in  $W^{1-\frac{1}{p}, p}(\partial\Omega)$ . Note that for a general boundary  $\partial\Omega$  without any type of regularity, one can define the space of traces as  $X = W^{1, p}(\Omega)/W_0^{1, p}(\Omega)$ ; assertion (15) then takes places in  $X'$ .

*Remark 2.* – When the function  $a$  is assumed to satisfy assumptions which are more general than (7) and (8), property (15) is no more true in general, but one can still prove (see [6], [7], [8]) that two solutions of (1) satisfy  $(a(x, u_1, \nabla u_1) - a(x, u_2, \nabla u_2)) n = 0$  on  $\partial\Omega$ .

**Proof of Theorem 1.1.** From Lemma 2.2 and  $f_1 \leq f_2$ , we deduce

$$\int_{\{u_2 < u_1\}} \left( a(x, u_2, \frac{du_2}{dx}) - a(x, u_1, \frac{du_1}{dx}) \right) \frac{d\varphi}{dx} dx \geq 0, \quad (16)$$

for every  $\varphi \in W^{1, p}(\Omega) \cap L^\infty(\Omega)$  with  $\varphi \geq 0$  a.e. in  $\Omega$ . Replacing  $\varphi$  by  $\varphi + \|\varphi\|_{L^\infty(\Omega)}$ , we deduce that (16) holds for every  $\varphi \in W^{1, p}(\Omega) \cap L^\infty(\Omega)$ , thus by density for every  $\varphi \in W^{1, p}(\Omega)$ , and (16) is therefore an equality and not only an inequality. Since in the one dimensional case every function of  $L^p(\Omega)$  is the derivative of a function of  $W^{1, p}(\Omega)$ , we get

$$\left( a(x, u_2, \frac{du_2}{dx}) - a(x, u_1, \frac{du_1}{dx}) \right) \chi_{\{u_2 < u_1\}} = 0 \text{ a.e. in } \Omega. \quad (17)$$

Adding and subtracting  $a(x, u_2, \frac{du_1}{dx})$  in (17), then multiplying by  $\frac{d(u_2 - u_1)}{dx}$  and using (6), (7) and  $\left| \frac{du_1}{dx} \right|^{p-1} \leq \left( \left| \frac{du_1}{dx} \right| + \left| \frac{du_2}{dx} \right| \right)^{p-1}$ , we obtain  $\left| \frac{d(u_2 - u_1)}{dx} \right| \leq \frac{\gamma}{\alpha} \left( \left| \frac{du_1}{dx} \right| + \left| \frac{du_2}{dx} \right| \right) |u_2 - u_1|$ , a.e. in  $\{u_2 < u_1\}$ . Then, for  $\varepsilon > 0$  and  $T_\varepsilon$  defined by (11), we deduce from Poincaré's inequality in  $W_0^{1, 1}(\Omega)$  (recall that  $u_1 \leq u_2$  on  $\partial\Omega$ )

$$\begin{aligned} |\{u_1 - u_2 > \varepsilon\}| &\leq \int_\Omega \frac{T_\varepsilon(u_1 - u_2)^+}{\varepsilon} dx \leq C \int_\Omega \left| \frac{d}{dx} \frac{T_\varepsilon(u_1 - u_2)^+}{\varepsilon} \right| dx = \\ &= \frac{C}{\varepsilon} \int_{\{0 < u_1 - u_2 < \varepsilon\}} \left| \frac{d(u_1 - u_2)}{dx} \right| dx \leq \frac{C\gamma}{\alpha} \int_{\{0 < u_1 - u_2 < \varepsilon\}} \left( \left| \frac{du_1}{dx} \right| + \left| \frac{du_2}{dx} \right| \right) dx. \end{aligned}$$

Taking the limit when  $\varepsilon$  tends to zero, we deduce  $|\{u_1 > u_2\}| = 0$ , and then  $u_2 \geq u_1$  a.e. in  $\Omega$ .  $\square$

**Proof of Theorem 1.2.** We assume that the sign of  $f_1$  is constant in  $\Omega$  (the other case is similar). Taking  $\varphi = 1$  in (12) for  $i = 1$ , we deduce that  $\langle f_1, T_\varepsilon(u_1 - u_2)^+/\varepsilon \rangle$  tends to zero when  $\varepsilon$  tends to zero. But when the sign of  $f_1 \in W^{-1, p'}(\Omega)$  is constant, it is well known that  $f_1$  can be identified with a nonnegative or nonpositive Radon measure which vanishes on the sets of zero  $W_0^{1, p}$ -capacity. Therefore one has  $f_1 \chi_{\{u_2 < u_1\}} = 0$ . Taking then  $\varphi = T_k(u_1)$  in (12) for  $i = 1$ , and passing to the limit when  $k$

tends to infinity, we get  $\int_{\{u_2 < u_1\}} a(x, u_1, \nabla u_1) \nabla u_1 dx = 0$ , which from (6) and  $a(x, s, 0) = 0$  (which results from (8)) implies that  $\nabla u_1 = 0$  a.e. in  $\{u_2 < u_1\}$ . By (9) this also implies  $\nabla u_2 = 0$  a.e. in  $\{0 < u_1 - u_2 < \varepsilon\}$  for each  $\varepsilon > 0$ , then in  $\{u_2 < u_1\}$ . Since  $u_1 \leq u_2$  a.e. on  $\partial\Omega$ , Poincaré's inequality yields  $\int_{\Omega} |(u_1 - u_2)^+|^p dx \leq C \int_{\{u_2 < u_1\}} |\nabla(u_1 - u_2)|^p dx = 0$ , which implies  $u_1 \leq u_2$  a.e. in  $\Omega$ .  $\square$

### 3. The case where $\Omega$ is unbounded

When  $\Omega$  is unbounded, the results given in the present Note continue to hold (with the same proofs) if the space  $W_0^{1,p}(\Omega)$  is replaced by an adequate space.

If  $1 < p < N$ , for any open set  $\Omega$ , we consider the space  $D_0^{1,p}(\Omega)$  obtained by completion of  $\mathcal{D}(\Omega)$  for the norm  $\|u\|_{D_0^{1,p}(\Omega)} = \|\nabla u\|_{L^p(\Omega)}$ . Then in (1) we replace  $W_0^{1,p}(\Omega)$  by  $D_0^{1,p}(\Omega)$ , and we take  $f$  in  $(D_0^{1,p}(\Omega))'$  and  $U_0$  such that  $\varphi U_0 \in W^{1,p}(\Omega)$ , for every  $\varphi \in \mathcal{D}(\mathbb{R}^N)$ , and  $\nabla U_0 \in L^p(\Omega)$ . This formulation corresponds to a Dirichlet boundary condition both on  $\partial\Omega$  and at infinity.

If  $1 < p < +\infty$ , we assume that there exists a ball  $B_R$  such that  $Cap_{1,p}(\Omega^c \cap B_R; B_{2R}) > 0$ . We define the space  $V_0^{1,p}(\Omega) = \{u : \varphi u \in W_0^{1,p}(\Omega), \forall \varphi \in \mathcal{D}(\mathbb{R}^N), \nabla u \in L^p(\Omega)\}$ , endowed with the norm  $\|u\|_{V_0^{1,p}(\Omega)} = \|\nabla u\|_{L^p(\Omega)}$ . Then in (1) we replace  $W_0^{1,p}(\Omega)$  by  $V_0^{1,p}(\Omega)$ , and we take  $f$  in  $(V_0^{1,p}(\Omega))'$  and  $U_0$  as above. This formulation corresponds to a Dirichlet boundary condition on  $\partial\Omega$  and to a Neumann boundary condition at infinity.

A further generalization could be to consider the Dirichlet boundary condition on a part of  $\partial\Omega$  and the Neumann boundary condition on its complementary, by a convenient modification of the definition of the space  $V_0^{1,p}(\Omega)$ .

In all these generalizations the above proofs remain unchanged since one can still use Poincaré's inequality in  $\Omega \cap B_S$  (with  $S$  large enough) for functions in  $V_0^{1,p}(\Omega)$ , or Sobolev's inequality for functions in  $D_0^{1,p}(\Omega)$ .

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